Wave-Ice Interaction in the Marginal Ice Zone: Toward a Wave-Ocean-Ice Coupled Modeling System

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LONG-TERM GOALS

Our main objective is to improve an operational model for wind-generated surface gravity waves (WAVEWATCH III®) such that it can accurately predict the attenuation and scattering of waves by interaction with ice in the Marginal Ice Zone (MIZ). The wave model physics developed here will later be part of an operational coupled model system, allowing feedback to ice, ocean, and atmospheric models.

OBJECTIVES

The specific objective of this proposal is to fully exploit the theoretical, observational, and ice/ocean/atmosphere numerical modeling work performed by various groups within the MIZ DRI and the "Sea State Sea State and Boundary Layer Physics of the Emerging Arctic Ocean" DRI to improve wave predictions.

APPROACH

The WAVEWATCH III model (Tolman 1991, Tolman et al. 2002, Tolman 2009) is a phase-averaged wave model solved by integrating the wave action conservation equation. Local rates of change of wave spectral density is determined by advection in four dimensions (two geographic and two spectral dimensions) and source terms representing various dynamic processes, such as energy transfer from the wind, and energy lost due to wave breaking. The present approach in WAVEWATCH III ("WW3") is to represent the effect of ice on waves as part of the advection, such that under partial ice cover, wave energy is partially blocked, with linear scaling of the blocked fraction according to ice concentration (Tolman 2003). This is a practical approach for an operational model, since present state of knowledge of wave-ice interaction hardly justifies more rigorous methods, especially not at the resolution at which the model is typically applied. In any case, ice concentration is the only ice variable traditionally available for input to the wave model in an operational environment. However,

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this approach has a number of drawbacks, e.g. it does not allow one intuitive outcome: that the attenuation rate of wave energy as it enters the MIZ should depend on wave frequency. Further, with research efforts such as the aforementioned DRIs now starting, it is reasonable to expect that the state of knowledge will improve soon; enough such that it is reasonable to begin thinking about new ways to represent these physics. Our plan is to implement these effects as source terms, rather than as a partial blocking of advection. The new source terms, S_{ice}, will be implemented in a manner consistent with the real ocean; these interactions consist of both conservative and non-conservative physics, $S_{ice} = S_{ice,c} + S_{ice,nc}$. The former will represent the scattering and reflection of waves by ice, and the latter will represent dissipation of wave energy by the ice, noting that for swell entering the MIZ, both source terms imply a diminishing of wave energy along the direction of propagation.

A summary of tasks is given below.

Task 1. WAVEWATCH-III interface. Implement the framework for the wave attenuation source term in WW3.

Task 2. Baseline wave hindcasts (basin-scale). Create baseline hindcasts for the entire Arctic basin, initially using traditional treatment of ice (Tolman 2003), and later to be applied with the new source terms.

Task 3. Sensitivity analysis. Determine reasonable range of values for free parameters of new physics using baseline hindcasts.

Task 4. Real part of wavenumber. Incorporate into WW3 the effect of sea ice on the real part of the wavenumber (determined by the physics routines for $S_{ice,nc}$), which produces an effect analogous to refraction and shoaling by bathymetry. (The imaginary part of the complex wavenumber determines the dissipation rate.)

Task 5. Non-dissipative scattering. Implement conservative source term $S_{ice,nc}$. This will be a diffusive scattering mechanism, whereby for each model frequency, there are two free parameters, controlling the strength of diffusion and fraction reflected, with both being quantified as "per unit time" or "per distance travelled".

Task 6. Baseline wave and ice hindcasts (regional). Similar to Task 2, except that these hindcasts would be for the focus area of the DRI, the Chukchi and Beaufort Seas, nested in the basin-scale simulations. This would provide the basis for further, deterministic modeling. A secondary motivation for these preliminary hindcasts is that they will establish a limited climatology for the incident swell directions, which can be considered when planning locations for in situ measurements, flight paths, etc. This task would include application of Community Ice CodE (CICE).

Task 7. Deterministic modeling. Using the sub-regional hindcasts, we will use physics-based relationships connecting ice concentration and floe size distribution to the coefficients required by the theoretical models to estimate, again leveraging expertise of external groups participating in the DRI.

Task 8. Breakup investigations. Observations of temporal variation of MIZ geographic extent and floe size distribution will be used with wave information to connect wave events with seasonal ice breakup events.

Task 9. Coupled Modeling System. We will introduce the new WW3 code with the source terms into a coupled modeling system implementation. NRL will perform ice/ocean/wave hindcasts for the Chukchi and Beaufort Seas with tight coupling via Earth System Modeling Framework (ESMF) interfaces in each model.

Task 10. Inversion for ice characteristics. We will utilize satellite, airborne and in situ wave observations to invert for necessary parameters (e.g. effective viscosity) using selected mathematical models and WW3 hindcasting for the DRI region.

WORK COMPLETED

Tasks 1 and 2 are completed, and Task 3 is partially completed.

WW3 was modified to allow up to eight new ice-related parameters to be read in from external files. The parameters are allowed to vary in time and space. Three methods were implemented for representation of $S_{ice,nc}$:

1) A simple routine in which the wave dissipation rate $k_i(x, y, t)$ is prescribed. With this method, k_i does not vary with wave frequency.
2) The method of Liu et al. (1991). This approach is based on the assumption that dissipation is caused by turbulence at the ice/water interface. The input parameters are ice thickness and an "eddy viscosity in the turbulent boundary layer beneath the ice".
3) The method of Wang and Shen (2010). This routine was provided by Prof. Hayley Shen (Clarkson University), who is also participating in the Sea State DRI. In this approach, sea ice is represented as a visco-elastic layer. Inputs are effective viscosity and a modulus of elasticity. This method takes approximately 10 times as long to solve as method (2), but it is a more physically plausible representation.

Work completed during CY2012 is documented in a report, Rogers and Orzech (2012). This report includes the following: explanation of WW3 input methods; review of situation with respect to operational wave modeling in the Arctic; description and discussion of existing methods of representing ice in WW3; description of methods (1) and (2) above; one-dimensional and two-dimensional testing; and a brief review of literature relevant to the prediction of attenuation of wave energy by sea ice. The testing described in the report verifies that the physics routines and methods of prescribing non-stationary and non-uniform ice parameters are working properly. Sensitivity to spatial resolution is analyzed. The report does not include a description of method (3), which was done in CY2013, and does not include validation (comparisons with observations); validation will be conducted during FY14.

The Science Plan for the Sea State DRI was constructed by the DRI PIs and is now available to the public (Thomson et al. 2013).

RESULTS

A baseline WW3 hindcast for the Arctic basin is shown in Figure 1. This corresponds to the Arctic cyclone of August 2012 described by Simmonds and Rudeva (2012), Zhang et al. (2013) and

Parkinson and Comiso (2013). Ten meter wind vectors and ice concentrations used as forcing for this hindcasts were taken from Navy operational products, NOGAPS (Navy Operational Global Atmospheric Prediction System, Hogan and Rosmond (1991); Rosmond et al. (2002)) and SSMI (radiometer) analysis, respectively. A polar stereographic grid (Rogers and Campbell 2009) is used. The figure shows significant waveheight (m) in color scaling, and ice concentration contours corresponding to 30, 50, and 70% for 2100 UTC 5 August 2012. Ice concentrations greater than 75% are treated as impermeable, and concentrations lower than 25% as open water; intermediate values are partially blocked with linear scaling using the conventional ice treatment of Tolman (2003). In this case, swells from the open ocean are disregarded in this simulation, but similar hindcasts have been performed by NRL for the boreal autumn 2010 using a mosaic system which includes a global grid, as implemented in WW3 by Tolman (2008) and adapted for irregular grids by NRL. These tests will be repeated using the new physics described above.

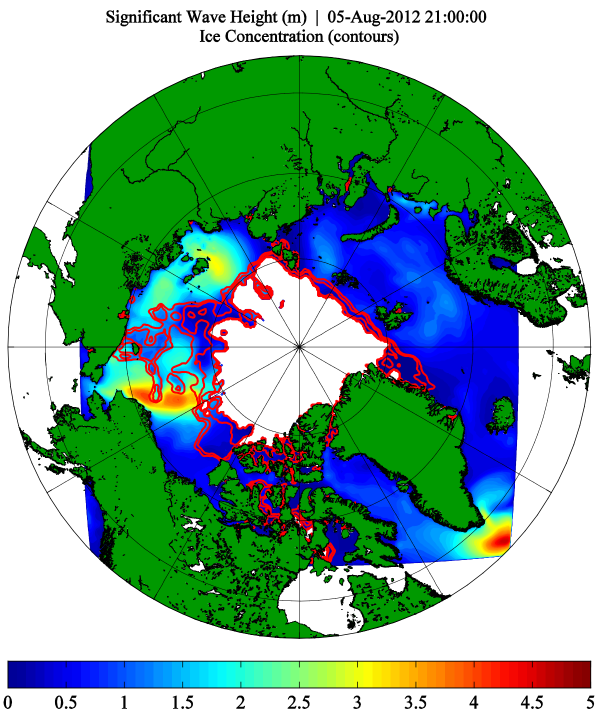

Figure 1. Significant wave heights (m) from a hindcast of the August 2012 storm.

These ongoing changes to the WW3 code are, in effect, a contribution to a community model. The code is maintained on NRL and NCEP (National Centers for Environment Prediction) SubVersion (version control) servers. The NCEP server is the repository used to manage code contributions from international developers, with the "trunk" being managed by NCEP personnel, and various "branches" being managed by individual developers. Distribution of the development code is strictly limited to the development group and associates approved by NCEP, but the trunk will serve as the basis for a public release scheduled for early 2014 (WW3 version 4). The WW3 code with new sea ice source functions is maintained in a branch by PI Rogers, and these changes will be merged into the trunk during Q4 of CY2013. The NRL repository is based on the NCEP trunk, with minor differences, and is used by NRL researchers in their modeling efforts, and is used to create "tag versions" to be evaluated and adopted

for Navy operations (FNMOC and NAVOCEANO, primarily). However, transition of these new capabilities to operations is beyond the scope of the present project.

IMPACT/APPLICATIONS

Improvement of the wave model skill in the Arctic is a goal on its own, but this improvement also enables and facilitates other research within the DRIs. The modified WW3 model will be a tool for studying the changing wave climate in the Beaufort and Chukchi Seas, and for interpreting observations collected via the DRIs. This is discussed in the summary of tasking above, and greater detail can be found in Thomson et al. (2013).

RELATED PROJECTS

PIs Rogers and Posey are funded by a separate project concurrent with the proposed project. This project is an NRL Core Advanced Research Initiative (ARI) led by Richard Allard (Section Head, NRL Code 7322) entitled, "Determining the Impact of Sea Ice Thickness on the Arctic's Naturally Changing Environment (DISTANCE)".

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PUBLICATIONS

Rogers, W. E., M. D. Orzech, 2013. Implementation and testing of ice and mud source functions in WAVEWATCH III®. NRL Memorandum Report, NRL/MR/7320-13-9462, 31pp. (http://www7320.nrlssc.navy.mil/pubs.php) [published]

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